

Small-x QCD physics probed with jets in CMS *

Pedro Cipriano[†] on behalf of the CMS Collaboration

Deutsches Elektronen-Synchrotron, Notkestrasse 85, 22607 Hamburg, Germany

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Abstract

The latest CMS jet measurements in p-p collisions at $\sqrt{s} = 7$ TeV, sensitive to small-x QCD physics, are discussed. These include inclusive forward jet and simultaneous forward-central jet production, as well as production ratios and azimuthal angle decorrelations of jets widely separated in rapidity.

1 Introduction

The measurement of forward jets provides an important testing ground for QCD predictions of the Standard Model in the low-x region. The LHC (Large Hadron Collider) can reach Q^2 and x values previously inaccessible to Hera as displayed in figure 1. To access the low-x region one must look at high rapidity. For such task the rapidity coverage of up to $|\eta| = 5.2$ in CMS [1] has been used.

The jet-rapidity and transverse-momenta is well described by the calculations at next-to-leading-order (NLO) in perturbative quantum chromodynamics (QCD) using the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) [2–6] approach and collinear factorization. The dijet cross-section is also well described [8]. When the collision energy \sqrt{s} is considerably larger than the hard scattering scale given by the jet transverse momentum, p_T , calculations in perturbative QCD require a resummation of large $\log(1/x)$ terms. This leads to the prediction of new dynamic effects, expected to be described by Balitsky-Fadin-Kuraev-Lipatov (BFKL) evolution [9–11] and k_T factorization [12–14]. An effective theory has been developed which describes strong interactions in this kinematic domain [15]. This description is particularly useful in events with several jets with large rapidity separation, which are not well described by DGLAP predictions.

To extend the study of the parton evolution equations, the azimuthal angle differences were also measured. This observable has a sensitivity to BFKL effects when both jets are widely separated in rapidity (eg: Mueller-Navelet jets).

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[†]pedro.cipriano@desy.de

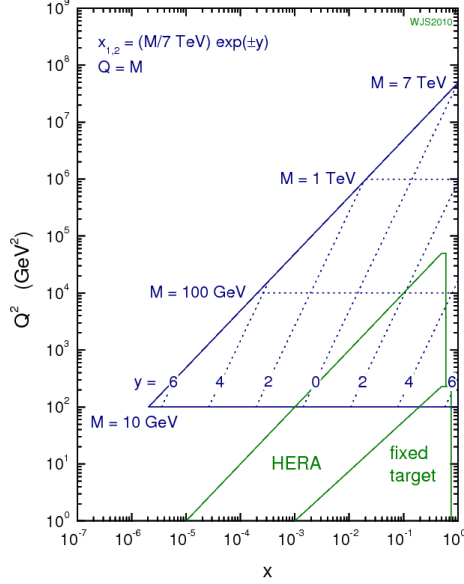


Figure 1: Kinematic phase-space accessible to Hera and LHC [7].

2 Inclusive forward jet production

The inclusive forward jet cross-section was measured from an integrated luminosity of 3.14 pb^{-1} [16]. Jets were reconstructed with the anti- k_T clustering algorithm [17, 18] with a distance parameter $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.5$. The energy depositions in the calorimeter cells were used as input for the clustering. Assuming massless jets, a four-momentum is associated with them by summing the energy of the cells above a given threshold.

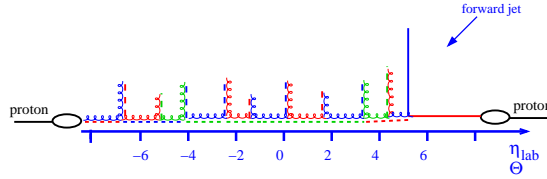


Figure 2: Feynman diagram for inclusive forward jet production

The forward region is defined as $3.2 < |\eta| < 4.7$. The jets are required to have a transverse momentum above $p_T = 35 \text{ GeV}$. If more than one jet is present, the one with highest p_T is considered, as is illustrated in figure 2. The jets are corrected for the following systematic effects: p_T and η -dependent response of the calorimeters, overlap with other proton-proton interactions and

the migration of events across the p_T bins due to jet energy resolution.

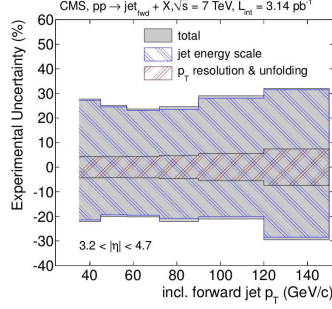


Figure 3: Inclusive forward jet production uncertainty [16].

In figure 3 the experimental systematic uncertainties are shown for the lead-ing forward jet as function of p_T . The jet energy scale is the dominant systematic uncertainty and the total uncertainty is around $-25+30\%$.

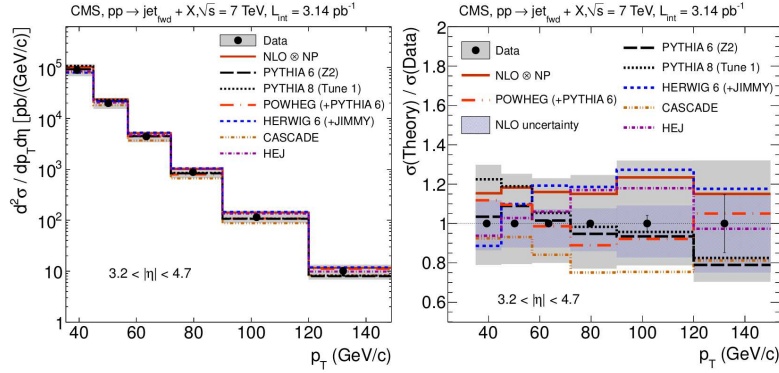


Figure 4: Inclusive forward jet cross-section compared with different Monte Carlo predictions [16].

The inclusive forward jet production cross-section corrected to hadron level is presented in figure 4. Although all predictions describe the data within the uncertainty band, some of them do better. POWHEG [19] + PYTHIA 6 [20] gives the best description. PYTHIA 6 and PYTHIA 8 [21] describe the data reasonably well. CASCADE [22] underestimates the cross-section while HERWIG 6 [23] + JIMMY [24] tends to overestimate. NLOJET++ overestimates the data but is still within the large theoretical and experimental uncertainties.

3 Forward-central dijet production

The selection procedure for the simultaneous forward–central dijet production is similar to the one for the inclusive forward jet production. In addition, a central jet within $|\eta| < 2.8$ with a transverse momentum above $p_T = 35$ GeV is required. A Feynman diagram of the process is shown in figure 5.

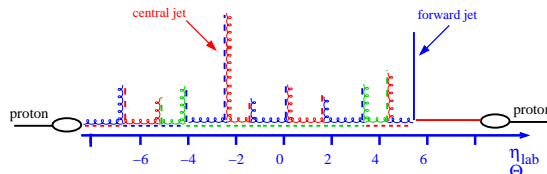


Figure 5: Feynmann diagram for forward–central dijet production

Several MC predictions compared to the data cross-section is presented in figures 6 and 7 [16]. Forward jet cross-section is steeper than the central jet. The shape of the forward jet is poorly described when compared with the central jet. HEJ [25] provides the best description being followed closely by HERWIG 6 and HERWIG ++ [26]. Both PYTHIA 6, PYTHIA 8 and the CCFM CASCADE have troubles describing the data for the central jets and for low p_T forward jets. POWHEG + PYTHIA 6, which was the best prediction for inclusive forward jet production, yields similar result as PYTHIA 6 alone.

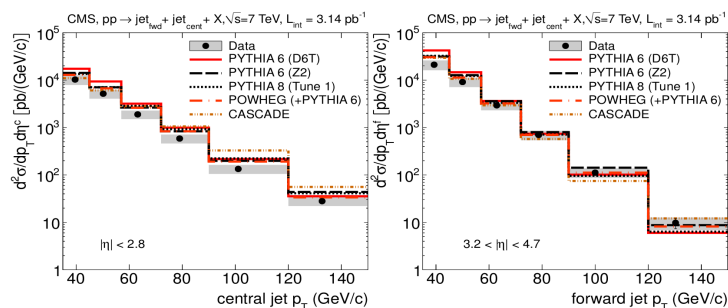


Figure 6: Forward–central dijet production compared with different Monte Carlo predictions [16].

4 Azimuthal–angle decorrelations of jets widely separated in rapidity

The reconstruction and correction procedure is similar as for the inclusive forward jet production [27]. Mueller-Navelet jets are the dijet pair with the highest

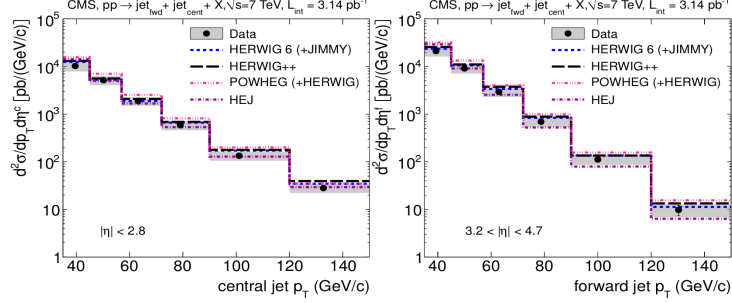


Figure 7: Forward–central dijet production compared with different Monte Carlo predictions [16].

rapidity separation. In this analysis only jets with p_T above 35 GeV and $|\eta| < 4.7$ were considered. The azimuthal angle decorrelations of jets widely separated in rapidity is presented in figures 8 and 9 as function of rapidity separation.

The first row of figure 8 displays the azimuthal angle difference $\Delta\phi$ for jets with a rapidity separation Δy less than 3. PYTHIA 6 and HERWIG ++ describe the data within uncertainties, while PYTHIA 8 and SHERPA 1.4 [28] with parton matrix elements matched show deviations at small and intermediate $\Delta\phi$. The second row shows $\Delta\phi$ for a rapidity separation between 3 and 6. HERWIG ++ provides the best description, but all predictions show deviation beyond the experimental uncertainties. The last row shows the azimuthal-angle difference for Δy between 6 and 9. The dijets are strongly decorrelated. HERWIG ++ provides the best description while PYTHIA 6 and PYTHIA 8 fail for the lower $\Delta\phi$ region.

The figure 9 shows $\Delta\phi$ for Mueller-Navelet jets with different rapidity separations compared with with different PYTHIA 6 predictions. The contributions of the angular ordering (AO) and multi-parton interactions (MPI) are very similar. The intermediate Δy region is better described without MPI. Overall the data is better described with AO and MPI.

5 Fourier coefficients ratio of the average azimuthal cosines

Using the same selection as in the previous section, the Fourier coefficients of the average cosines have been measured [27] and is presented in the figure 10.

$$C_n : d\sigma/d(\Delta\phi) \sim \sum C_n; \quad C_n = \langle \cos(n(\pi - \Delta\phi)) \rangle \quad (1)$$

DGLAP contributions are expected to partly cancel in the C_{n+1}/C_n ratio, which are described the by LL DGLAP-based generators towards low Δy .

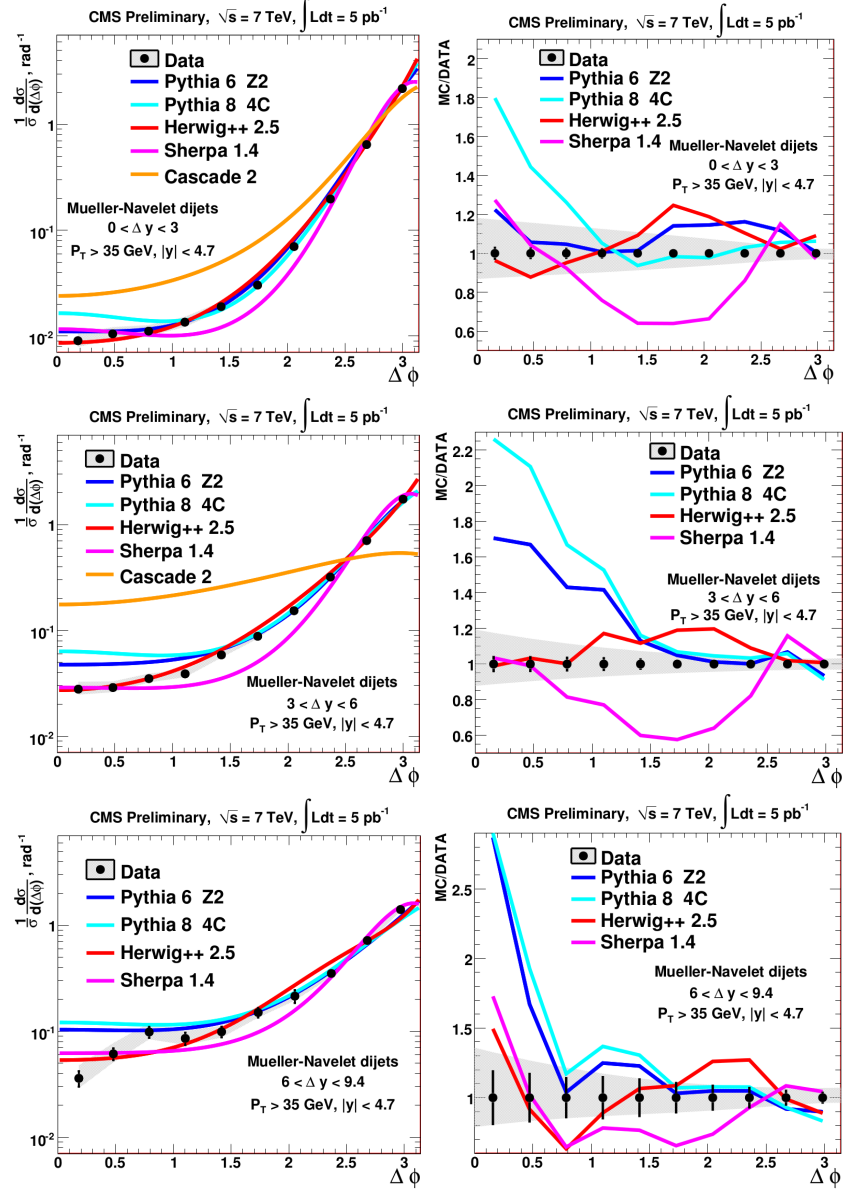


Figure 8: Azimuthal-angle decorrelations of jets widely separated in rapidity compared with different Monte Carlo predictions [27].

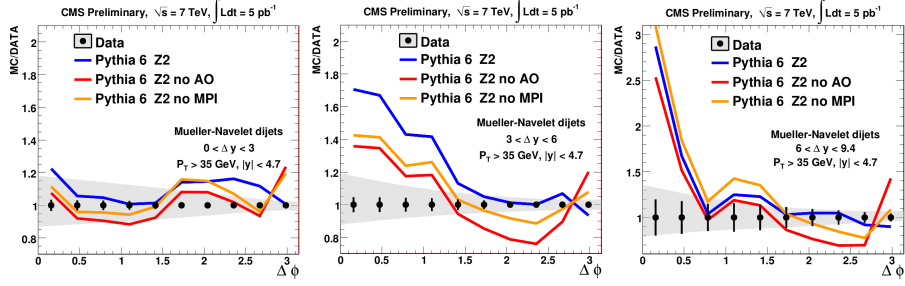


Figure 9: Azimuthal angle decorrelations of jets widely separated in rapidity compared with different PYTHIA6 predictions [27].

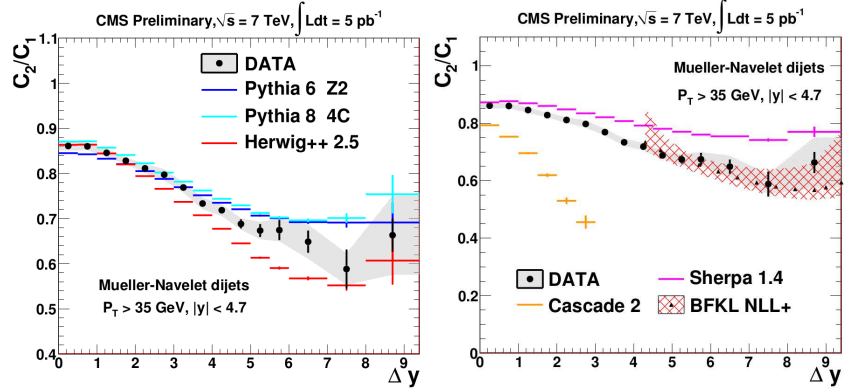


Figure 10: Fourier coefficients ratio of the average azimuthal cosines compared with different Monte Carlo predictions [27].

SHERPA, PYTHIA 8 and PYTHIA 6 overestimate C_2/C_1 while HERWIG underestimates it. The CCFM-based CASCADE predicts too small C_{n+1}/C_n . At $\Delta y > 4$, a BFKL NLL calculation describes C_2/C_1 within uncertainties.

6 Ratios of dijets production

Using jets with $p_T > 35$ GeV and $|\eta| < 4.7$ the ratio of the inclusive to exclusive dijet production was measured as a function of Δy [29]. With increasing Δy a larger phase-space for radiation is opened. The inclusive dijet sample consists of events with at least 2 jets over the threshold and exclusive requires exactly two jets. The ratio of inclusive to exclusive dijet production is shown in the figure 11. PYTHIA 6 and PYTHIA 8 agree well with the data while HERWIG ++ and HEJ + ARIADNE [30] overestimate the data at higher Δy . CASCADE is completely off. MPI gives only a small contribution.

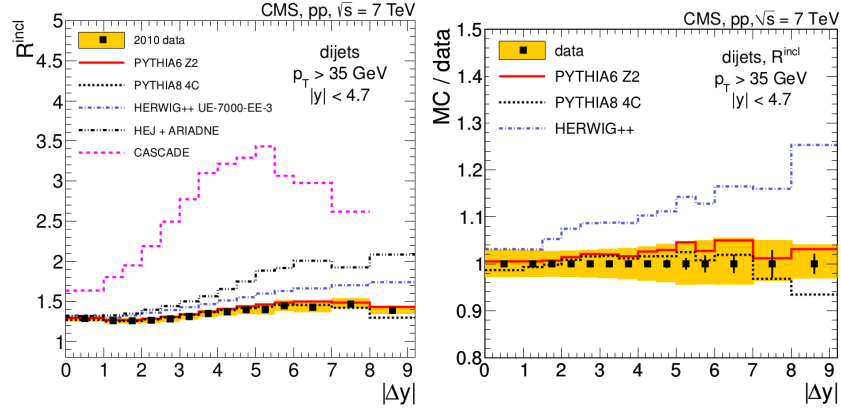


Figure 11: Ratios of inclusive/exclusive dijets production compared with different Monte Carlo predictions [29].

The ratio of inclusive to exclusive Mueller-Navelet dijets is presented in 12. At low Δy the ratio of Muller-Navelet over exclusive is, by definition, smaller than inclusive over exclusive and at higher Δy it is the same. The conclusions of the comparison between data and MC are the same as for the ratio inclusive over exclusive.

7 Summary

Inclusive measurements of forward and central-forward jets, are reasonably well described by the MC predictions while more exclusive measurements are poorly described. A summary of the MC description is presented in table 1. The DGLAP-based generators, PYTHIA and HERWIG, seem to do a better job than

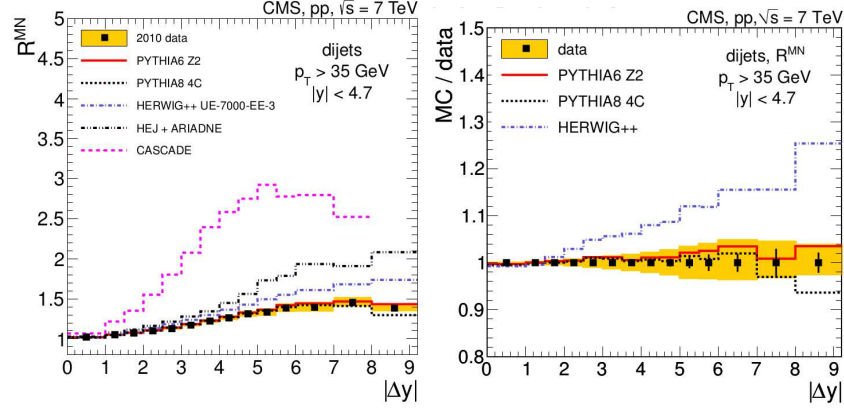


Figure 12: Ratios of Mueller-Navelet/exclusive dijets production compared with different Monte Carlo predictions [29].

the BFKL-inspired CASCADE. The effort of description of the underlying events, development of the parton showers and tuning of PYTHIA and HERWIG play an huge role into this result.

Observable	PYTHIA	HERWIG	CASCADE	HEJ
Forward jet p_T	Good	Acceptable	Acceptable	Good
Central-forward jet p_T	Bad	Acceptable	Bad	Good
Azimuthal correlations	Acceptable	Good	Bad	–
Fourier coefficients ratio	Acceptable	Bad	Bad	–
Dijet ratios	Good	Acceptable	Bad	Bad

Table 1: Monte Carlo description of the measurements

Acknowledgements

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